LOW-CYCLE FATIGUE AND CRACKING RESISTANCE OF POWER PLANT BOILER PIPES AND STEAM LINES OF 12Kh1MF STEEL

V. G. Zelenskii, A. V. Fedoseenko,
V. A. Sarkisyan, and V. V. Sevryugin

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Components of steam lines belong to the group of important components of power plants subjected to the highest stresses. Their reliability and service life are determined to a large extent by the crack resistance of their metal and by its low-cycle fatigue resistance in nonstationary service conditions.

12Kh1MF steel is used extensively in Soviet power engineering for the manufacture of steam lines and pipe components of steam generators. In the present work, the low-cycle fatigue and cracking-resistance characteristics of this steel were examined by testing specimens and full-size sections of steam lines produced from a single industrial batch of pipes with an external diameter of 194 mm and a wall thickness of 36-39 mm.

In addition to the low-cycle fatigue and cracking resistance test, the steel was also subjected to standard long-term strength tests and its chemical composition and mechanical properties were determined. As shown by the investigations, the chemical composition, mechanical properties, and creep strength characteristics of the metal of the examined pipes satisfied the technical requirements on the supply of steam lines and varied on the level of mean grade values. For example, the tensile strength of the metal of the specimens and experimental sections of the steam lines at a temperature of 565°C was equal to 255-274 MPa (26-28 kgf/mm^2), the yield stress was 206-235 MPa (21-24 kgf/mm^2), the relative elongation equalled 42%, the long-term strength limit for $1 \cdot 10^5$ h was 83 MPa (8.5 kgf/mm^2), and relative reduction in area in long-term (10-600 h) rupture was equal to 75-80%.

The steam-line pipes were tested in a special testing unit at a constant stress amplitude. In the tests, steam with a temperature of 560-565°C was fed into the pipes at a pressure of 19.6-21.7 MPa (200-222 kgf/cm^2) and a bending moment simulating compensating loads in the steam lines was applied to the pipes. The steam parameters were maintained constant during the experiments, and the bending moment developed by hydraulic servomotors was varied in accordance with a symmetric cycle with a period of 3 min. The loading diagram of the experimental sections of the steam lines is shown in Fig. 1.

The magnitudes of the relative strain in the metal of the pipes and the bending moment were determined in advance in calculations and then determined more accurately by strain gaging and deflection measurements. The relative strain in the metal of the pipes in section L where the bending moment is identical was calculated from the maximum deflection h using the equation

$$\varepsilon = \frac{D_0}{h + \frac{L^2}{4h}},$$

where D_0 is the outer diameter of the pipe.

To determine the number of cycles to the appearance of surface cracks and obtain the cracking-resistance characteristics of metal, the tested pipes were periodically examined during the experiments, their surface condition was inspected, and the length and depth of cracks measured. The depth of cracks was measured with an IGT-2-VTI device using the method described in [1]. The measurements and data obtained for special sections of pipes tested under the effect of bending loads showed that the crack front propagates along a circular chord and, consequently, the relationship between crack depth l and its length on the outer surface of the pipe α_d is determined by the following equation

$$l = \frac{D_0}{2}\left(1 - \cos \frac{180\alpha_d}{\pi D_0}\right).$$

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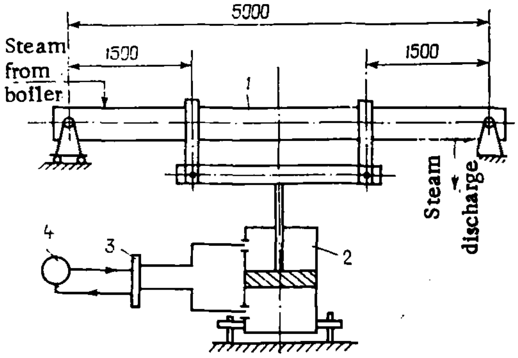

Fig. 1. Diagram of loading steam lines pipes in tests in the testing unit: 1) tested pipe; 2) hydraulic drive; 3) slide valve; 4) pump.

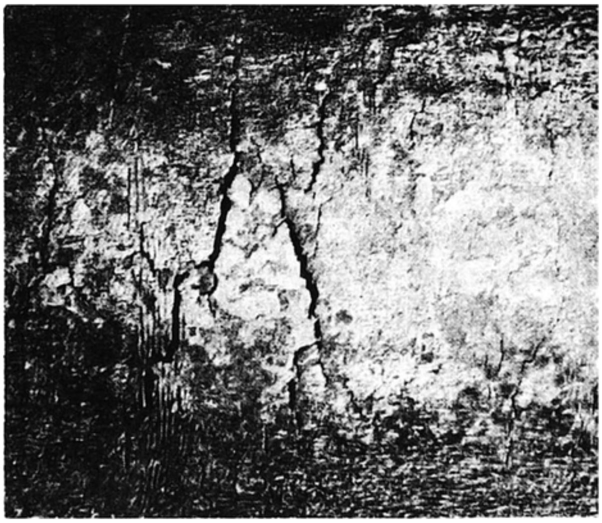

Fig. 2. External appearance of deep cracks on the outer surface of the steam line pipe.

The results of the tests on the steam-line sections of the pipes, characterizing their life to the appearance of through and surface cracks with a depth of up to 4 mm, are presented in Table 1.

As in the cases of damage in industrial steam lines, failure of the tested steam-line pipes on all the stress levels was of strainless nature (Fig. 2). No changes in the diameter and thickness of the pipes were detected in the areas of crack formation.

The life of the full-size steam-line pipes, determined by the ratio of the number of cycles of load variation to fracture after the appearance of a crack to the total number of cycles, depends, as shown by the investigations, on the stress level and is equal to approximately 0.2-0.5.

The results of the tests on the steam-line pipes presented in Table 1 are in satisfactory agreement with the data obtained in identical tests on specimens of boiler pipes made on 12Kh1MF steel with a diameter of 36 mm and a wall thickness of 6 mm (Fig. 3). The properties of the metal of these tubes also satisfied the requirements of the technical conditions. The tensile and yield strengths and relative elongation at a temperature of 560-565°C were equal to respectively 338 and 284 MPa (34 and 29 kgf/mm^2) and 42%.

The outer diameter of the specimens produced from these pipes was 28 mm and their wall thickness was 4 mm. The specimens were loaded with an alternating bending moment whose magnitude was determined on the basis of the strain in the specimens measured by mechanical strain gages. The period of a single cycle of load variation was 3 min. The tests were continued to the appearance of a through crack in the specimens. The number of cycles and time

TABLE 1. Results of Endurance Tests on Steam-Line Pipes with a Diameter of 194 mm and a Wall Thickness of 36 mm

Strain amplitude, %	No. of cycles		Life $\frac{N_2-N_1}{N_2}$
	to crack formation N_1	to fracture N_2	
0,130	8842	10858	0,19
0,158	4000	5600	0,29
0,180	2600	4100	0,37
0,196	2500	—	—
0,226	1500	2500	0,40
0,287	730	1450	0,49

TABLE 2. Experimental Data on the Rate of Crack Propagation in Tests of Steam Line Pipes

Stress amplitude, MPa (kgf/mm²)	Stress intensity $\frac{\Delta K}{1-r}$ MPa·m$^{1/2}$ (kgf/mm$^{3/2}$)	No. of cycles to fracture N_2-N_1	Crack propagation rate·10^{-5}, m/cycle
208 (21,2)	47,8 (154)	2016	1,76
219 (22,3)	50,3 (162)	1600	2,21
228 (23,3)	52,5 (169)	1500	2,32
245 (25,0)	56,5 (182)	1000	3,55
269 (27,4)	54,6 (176)	720	3,47

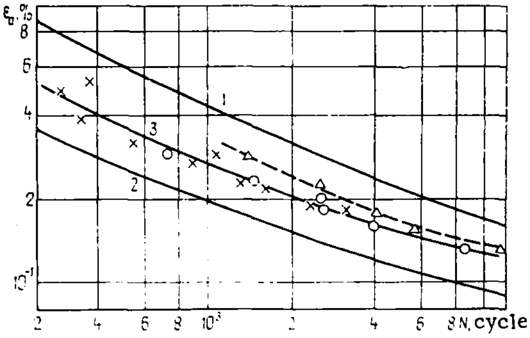

Fig. 3. Experimental and calculated data on the cyclic strength of pipes and specimens of 12Kh1MF steel: 1) the calculated curve for $\gamma = 1$; 2) the same for $\gamma = 0.39$; 3) experimental curve corresponding to the calculated curve at $\gamma = 0.6$ (×, experimental points obtained in testing specimens of pipes with a diameter of 36 mm and a wall thickness of 6 mm; ○, experimental points in testing the life of pipes with a diameter of 194 mm and a wall thickness of 36 mm to the formation of cracks 4 mm deep; Δ, the same, to the formation of through cracks).

to appearance of such a crack were determined from the reduction of the nitrogen pressure in the internal cavity of the specimens; at the start of the experiments, this pressure was set at 0.5-1.0 MPa (5-10 kgf/cm²). Heating of the specimens to temperatures of 560-565°C was carried out in electric furnaces.

In addition to the experimental points obtained in testing the steamline pipes with a diameter of 194 mm and a wall thickness of 36 mm, and the specimens of boiler pipes with a diameter of 36 mm and a wall thickness of 6 mm, Fig. 3 also gives the calculated curves constructed on the basis of the previously derived dependence [2] characterizing the low-cycle fatigue of boiler steels in the conditions of creep and stress relaxation

$$\sigma_a = \frac{2.3\gamma \cdot E_t}{4\sqrt{N}} \lg \frac{100}{100-\psi_t} + 0.8\frac{1-r}{2}\sigma_d,$$

TABLE 3. Results of Cracking Resistance Tests on Flat Specimens

Test temperature, °K (°C)	Stress intensity $\frac{\Delta K}{1-r}$, MPa·m$^{1/2}$ (kgf/mm$^{3/2}$)	Crack propagation rate ·10^{-6}, m/cycle
833 (560)	10,9 (35,2)	0,203
833 (560)	14,1 (45,5)	0,363
833 (560)	14,5 (46,8)	0,341
833 (560)	14,6 (46,9)	0,839
293 (20)	22,8 (73,4)	0,025
293 (20)	23,0 (74,2)	0,052
293 (20)	26,7 (86,1)	0,059
293 (20)	27,7 (89,3)	0,105
293 (20)	28,0 (90,1)	0,176

where N is the number of cycles; E_t and ψ_t are the modulus of elasticity and calculated relative reduction in area equal to half the sum of the uniform and maximum elongation of the specimens in the tensile test at corresponding temperatures; σ_d is the long-term strength limit; γ is the coefficient taking into account the effect of creep [3]; r is the cycle asymmetry ratio (stress ratio).

The following mean grade values of the properties of 12Kh1MF steel at 560°C were taken into account in constructing the curves: $E_t = 17.2 \cdot 10^4$ MPa ($1.76 \cdot 10^4$ kgf/mm^2); $\sigma_d = 82.3$ MPa (8.4 kgf/mm^2); $\psi_t = 40\%$.

Curve 1 in Fig. 3 was constructed for $\gamma = 1$ at which the effect of creep can be ignored. The limiting value of γ, which, according to our data, is equal to 0.39, is described by the curve 2. The experimental points are distributed between the above-mentioned calculated curves and are described by curve 3 for which $\gamma \simeq 0.6$. This value of coefficient γ at a cycle period of 3 min is confirmed by the examination of the strain capacity of the examined steel grade in cyclic loading in the creep conditions [3].

The stress intensity factor K_1 at which cracks propagated in the pipes was determined using the dependence

$$K_1 = \sigma \sqrt{\pi l} \cdot \mu,$$

where μ is a coefficient which depends on the ratio of crack depth to the outer diameter of the pipe l/D_0; according to [4], for the given standard size, the value of μ was assumed to be equal to 0.86-0.89.

The data presented in Table 2 show that the crack propagation rate in the steam-line pipes in the tests at a mean crack depth of 13-17 mm was high – $(1.76\text{-}3.5) \cdot 10^{-2}$ mm/cycle. This high crack propagation rate was caused by the high value of the stress intensity factor and strong effect of the creep processes.

In examining the crack resistance characteristics of the metal of the steam lines, the tests to fracture of the full-size pipes in type UM-10T machines were accompanied by tests on flat specimens with a cross section of 7 × 18 mm with a central crack in cyclic tension–compression. The magnitude of the maximum stresses in the cycle was equal to 0.8 $\sigma_{0.2}$. The stress intensity factor in testing the flat specimens was determined in accordance with the requirements of RD50–260–81 from the equation

$$K_1 = K_Q = \frac{P_Q}{t\sqrt{b}} Y_{2c},$$

where t and b are the thickness and width of the specimens; Y_{2c} is the function which depends on the ratio of crack depth to the width of the specimen; K_Q is the assumed value of the stress intensity factor at calculated load P_Q.

As shown by the tests on the flat specimens (Table 3), the crack propagation rate at a temperature of 560°C is considerably higher than that at 20°C. In the K_1 variation range from 21.7 to 27.9 MPa·m$^{1/2}$ (from 70 to 90 kgf/mm$^{3/2}$) these rates differ up to 30 times.

In conclusion, it should be mentioned that the low-cycle fatigue and cracking resistance characteristics represented in this work can be regarded as the representative characteristics for evaluating the endurance and volume of inspection of the steam lines and pipe components of power plant because they were determined on the metal of the full-size standard pipes in the conditions similar to those in service.

If it is taken into account that the equivalent stresses from internal pressure, self-compensation, and weight loads in steam lines permitted by OST 108.031.02–75 may reach the long-term strength limit, and the stress concentration in the areas of transitions, holes, tee joints and other elements is equal to approximately three, then the data in Tables 1 and 2 and Fig. 3 actually reflect the probability parameters of the rate of defect propagation and endurance of the components of the steam lines made of 12Kh1MF steel in areas of their geometrical heterogeneity. In straight sections of the steam lines, the parameters of endurance and crack propagation rate are an order of magnitude higher. For example, as a result of calculation processing of the previously examined experimental data it was established that the rate of propagation of crack-like defects with a depth of up to 2 mm, which can be passed in inspection of straight sections of steam lines of various standard dimensions in 12Kh1MF steel, is equal to $(0.6\text{-}1.0)\cdot 10^{-4}$ mm/cycle and in the areas with stress concentration it is equal to $(1.0\text{-}2.0)\cdot 10^{-3}$ mm/cycle.

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EXAMINATION OF THE CRACKING RESISTANCE OF CORROSION-RESISTING GLASS-REINFORCED PLASTICS BY ACOUSTIC EMISSION METHODS

V. N. Naumets, A. T. Nikiforov,
I. S. Guz', V. V. Bulakh,
L. T. Berezhnitskii, and L. V. Nagirnyi

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It was shown in [1, 2] that cracking resistance is one of the main characteristics of the efficiency of corrosion-resisting glass-reinforced plastics (CRGP), and comparable values of stress intensity factors K_Q were determined for discretely reinforced structures of the CRGPs (K_Q is the cracking resistance of thin and flat specimens with respect to the start of crack propagation which is not always equal to K_{Ic}).

It was assumed that the fracture toughness of the composites which reflects the resistance of the material to crack propagation does not characterize unambiguously its cracking resistance because it does not determine the resistance of the material to crack formation (K_0).

The concept of macrostresses developed by M. Ya. Leonov and K. P. Rusinko [3, 4] was used as a basis for deriving a number of variants of the relationship between the values of K_0 and K_{Ic} [5-8].

For a material with randomly distributed microcracks, the resistance to macrocrack initiation is

$$K_0 \approx 0.66K_{Ic}. \qquad (1)$$

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